Steelhead Life History Modeling

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Thinking about steelhead life history

- Why mature as resident?
  - Avoid ocean mortality
  - Potentially easier iteroparity
- Why smolt and emigrate?
  - Much larger size > higher reproductive success
- Why take action when young?
  - Less cumulative risk of mortality in stream
- Why take action when older?
  - Larger size at spawning = higher reproduction
  - Larger size at emigration = higher survival

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Model algorithm

- Postulates existence of “decision windows”
- Assess current size and potential for future growth as parr
- Assess expected fitness if smolt/mature at current size
- Compare with expected fitness of growing to a larger size and making an optimal decision in the future
- (discount for mortality)
- Model currently developed for females
- Assumes plastic response governed by heritable thresholds

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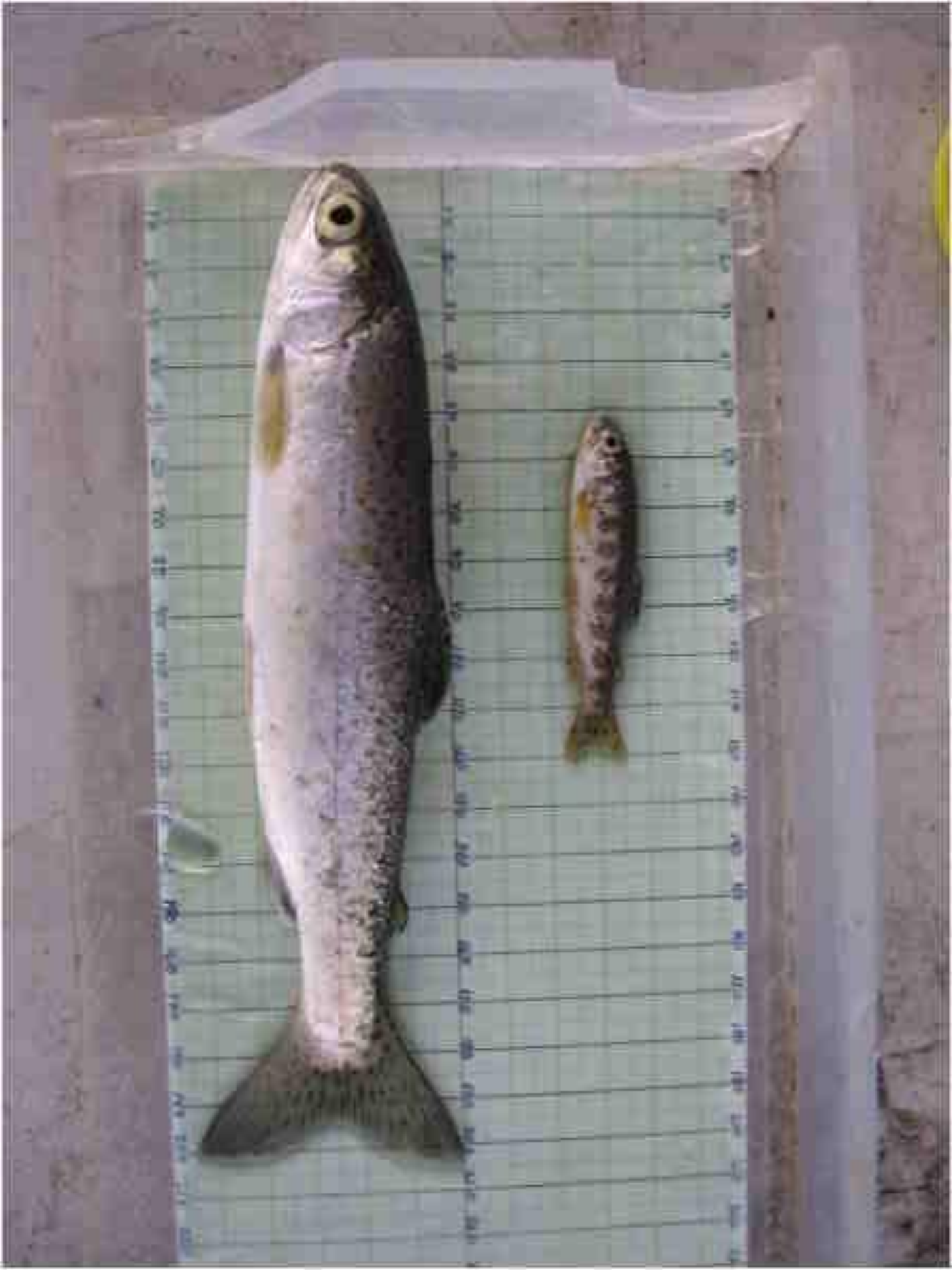
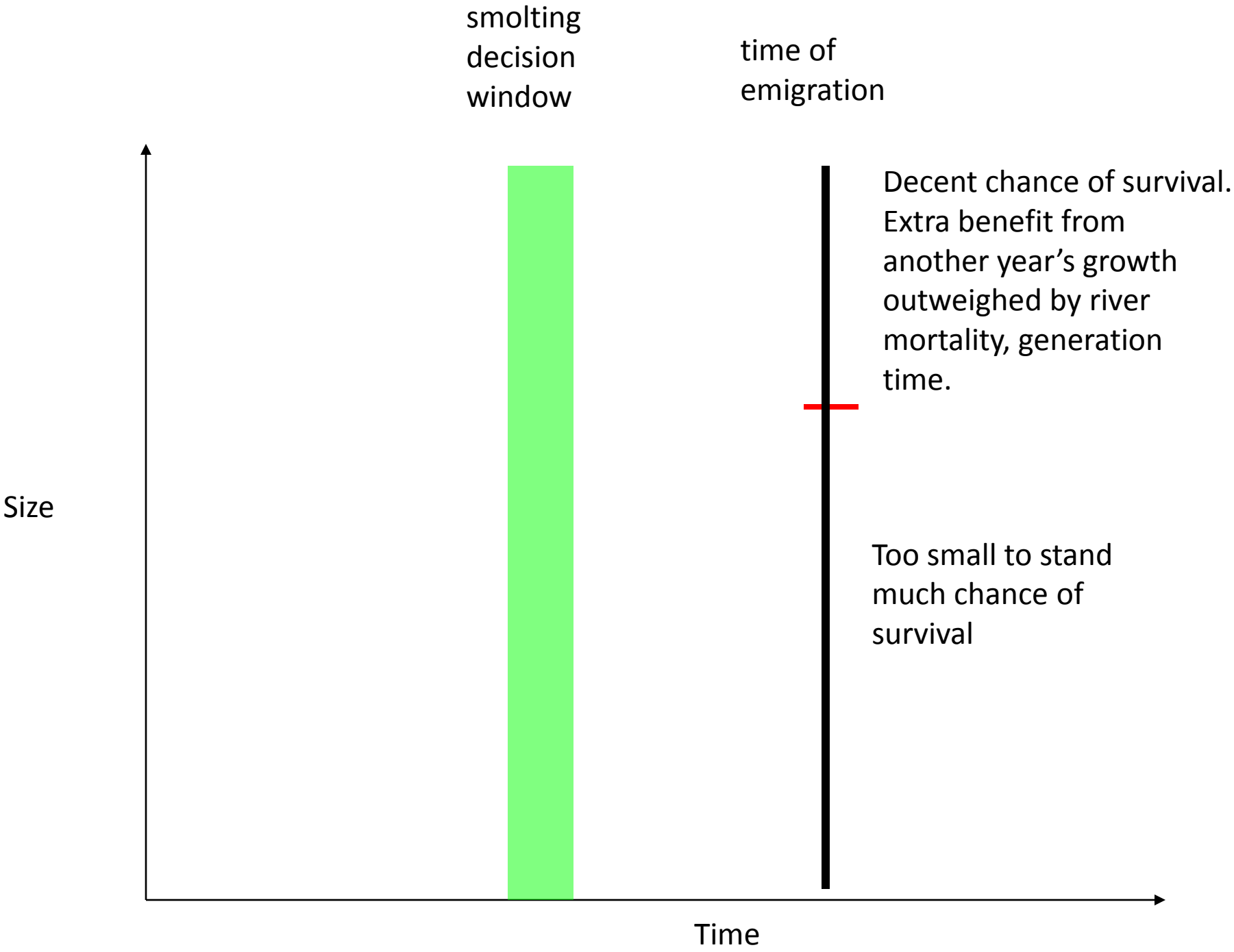
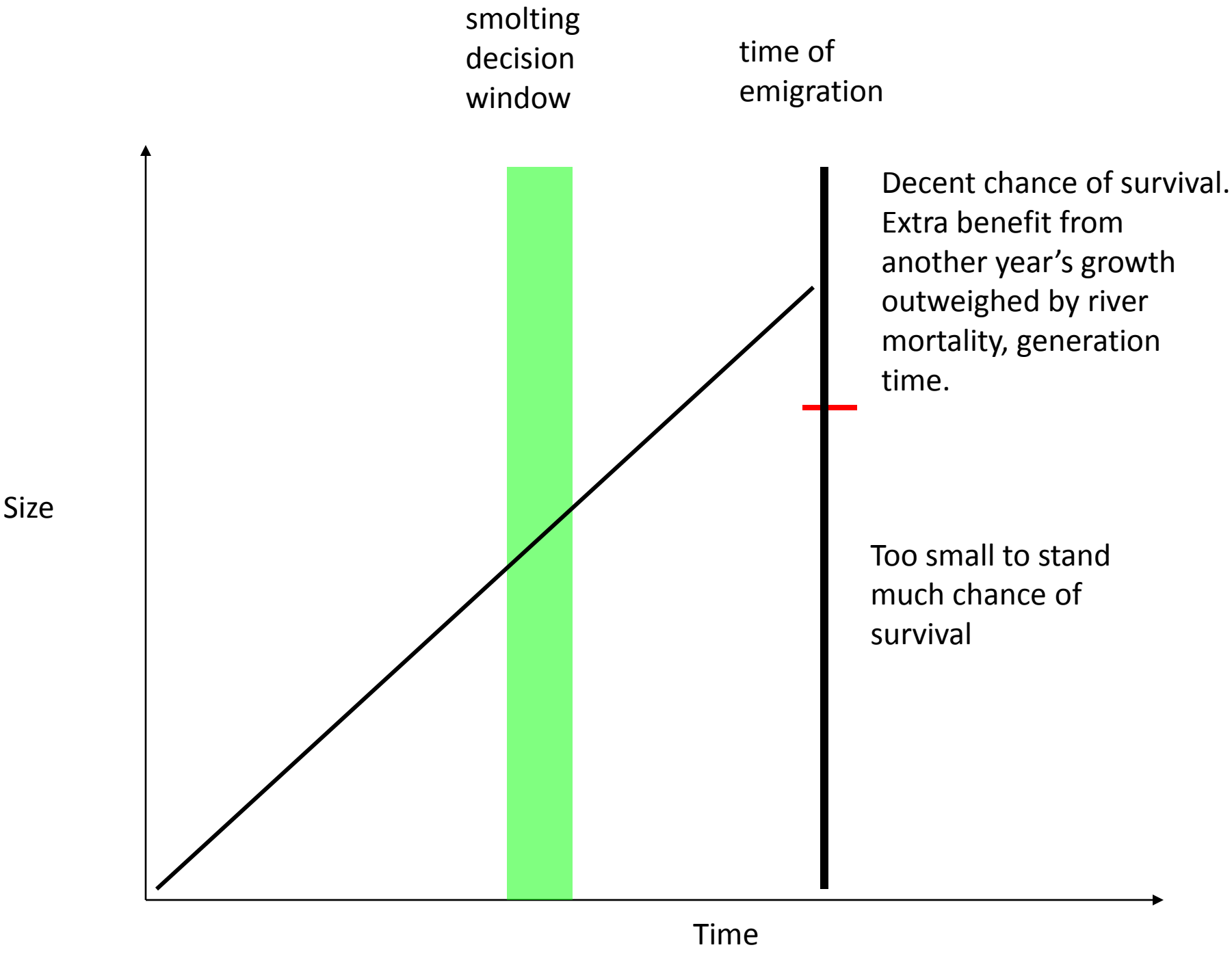



smolting decision window
time of emigration
Decent chance of survival. Extra benefit from another year's growth outweighed by river mortality, generation time.
Too small to stand much chance of survival
Size
Time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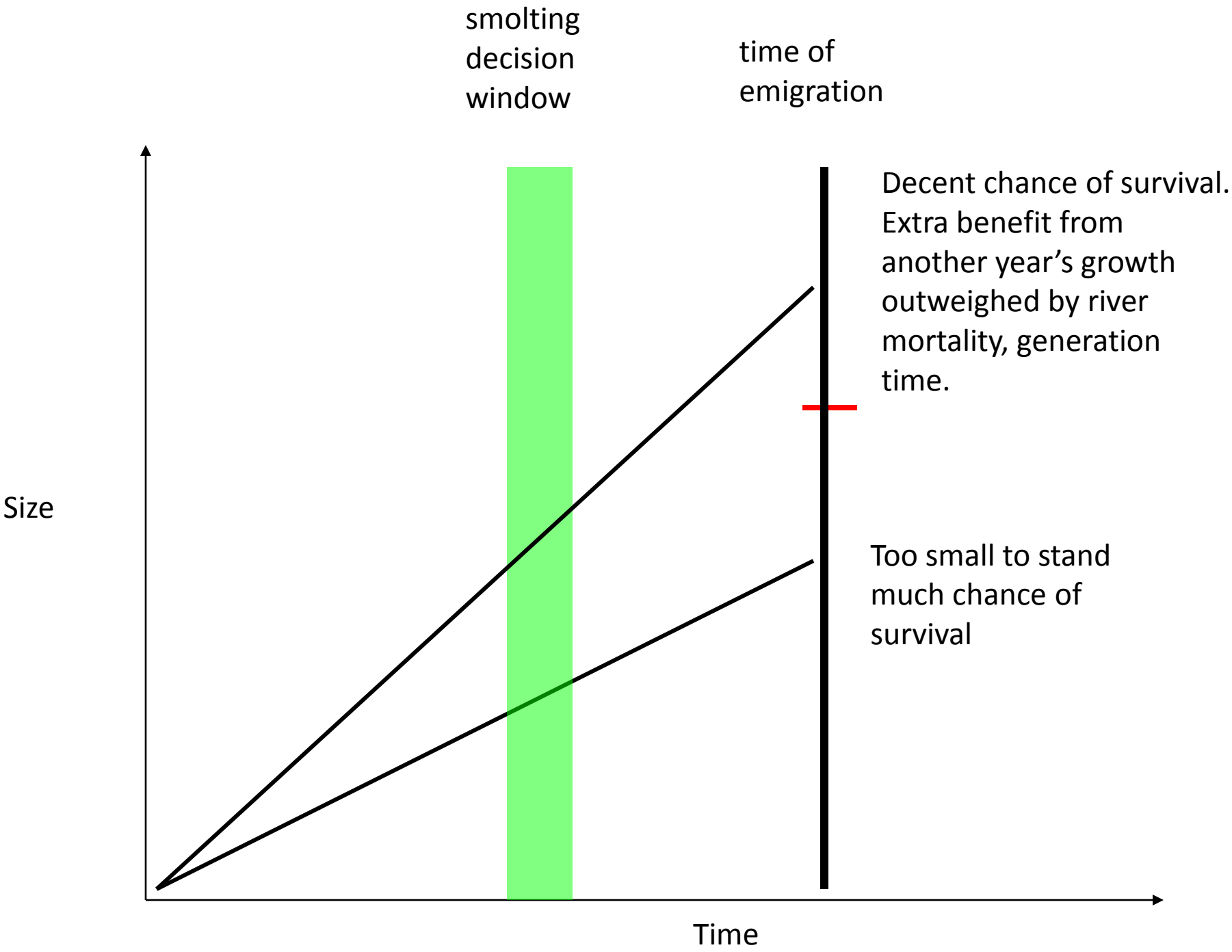
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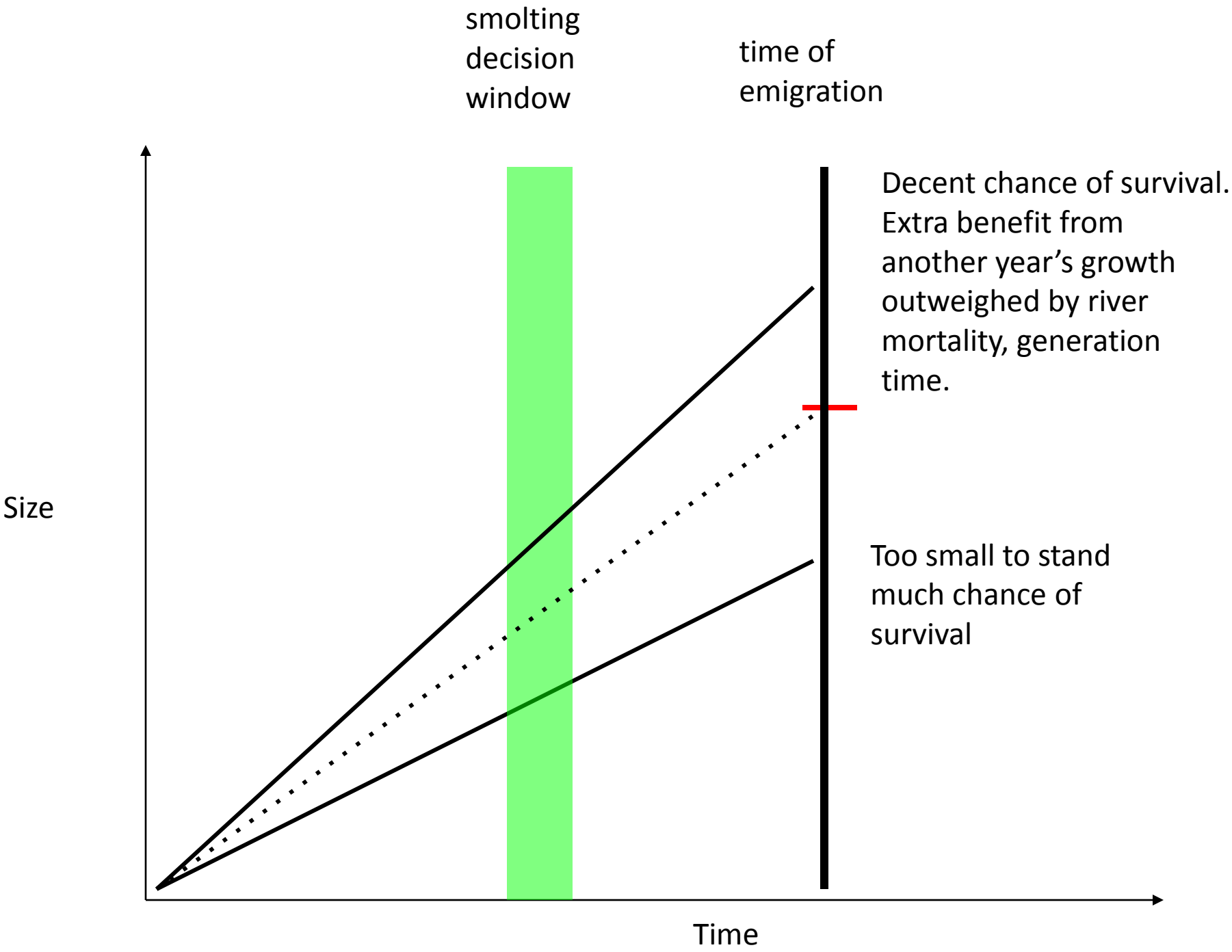
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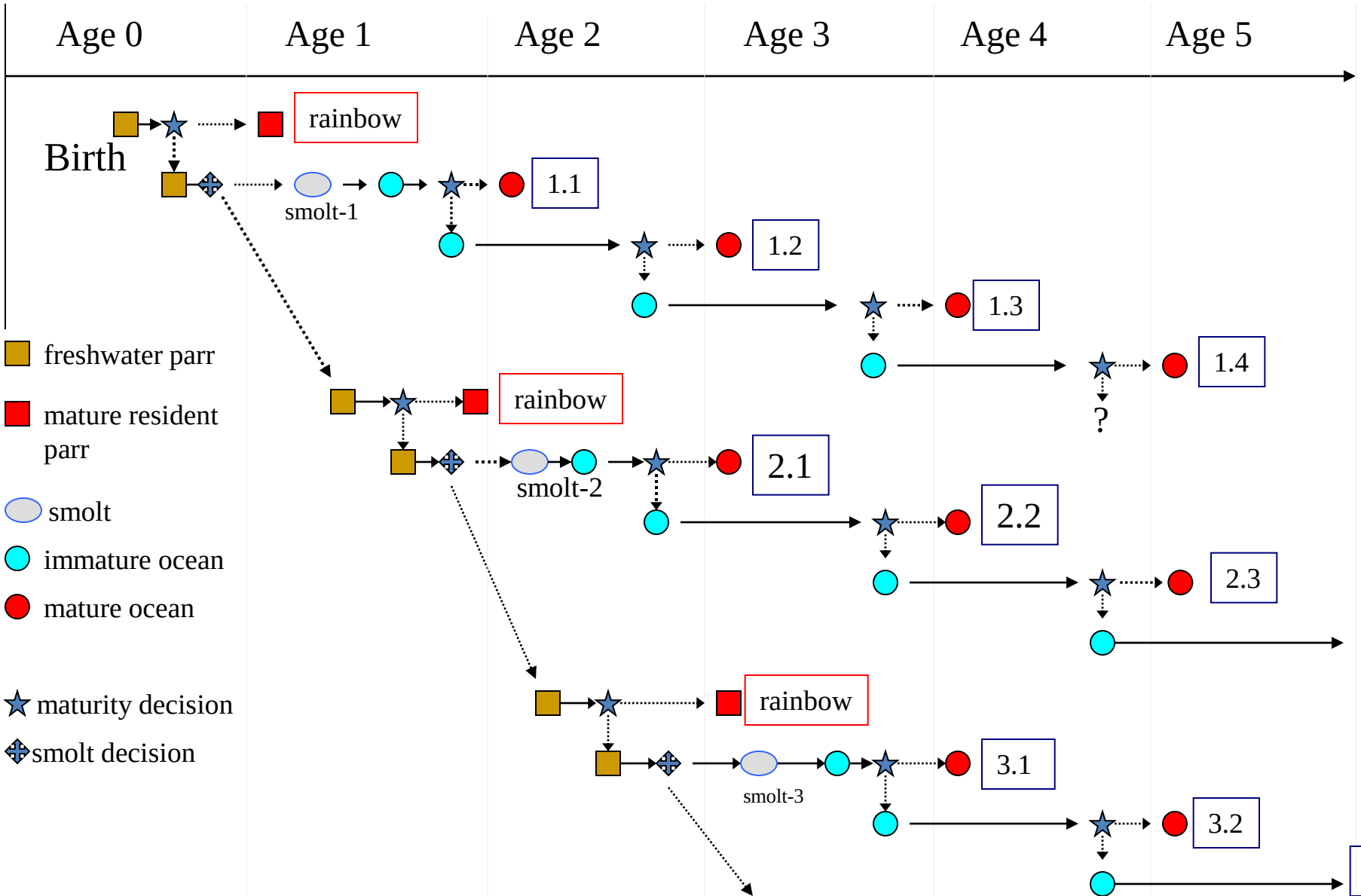
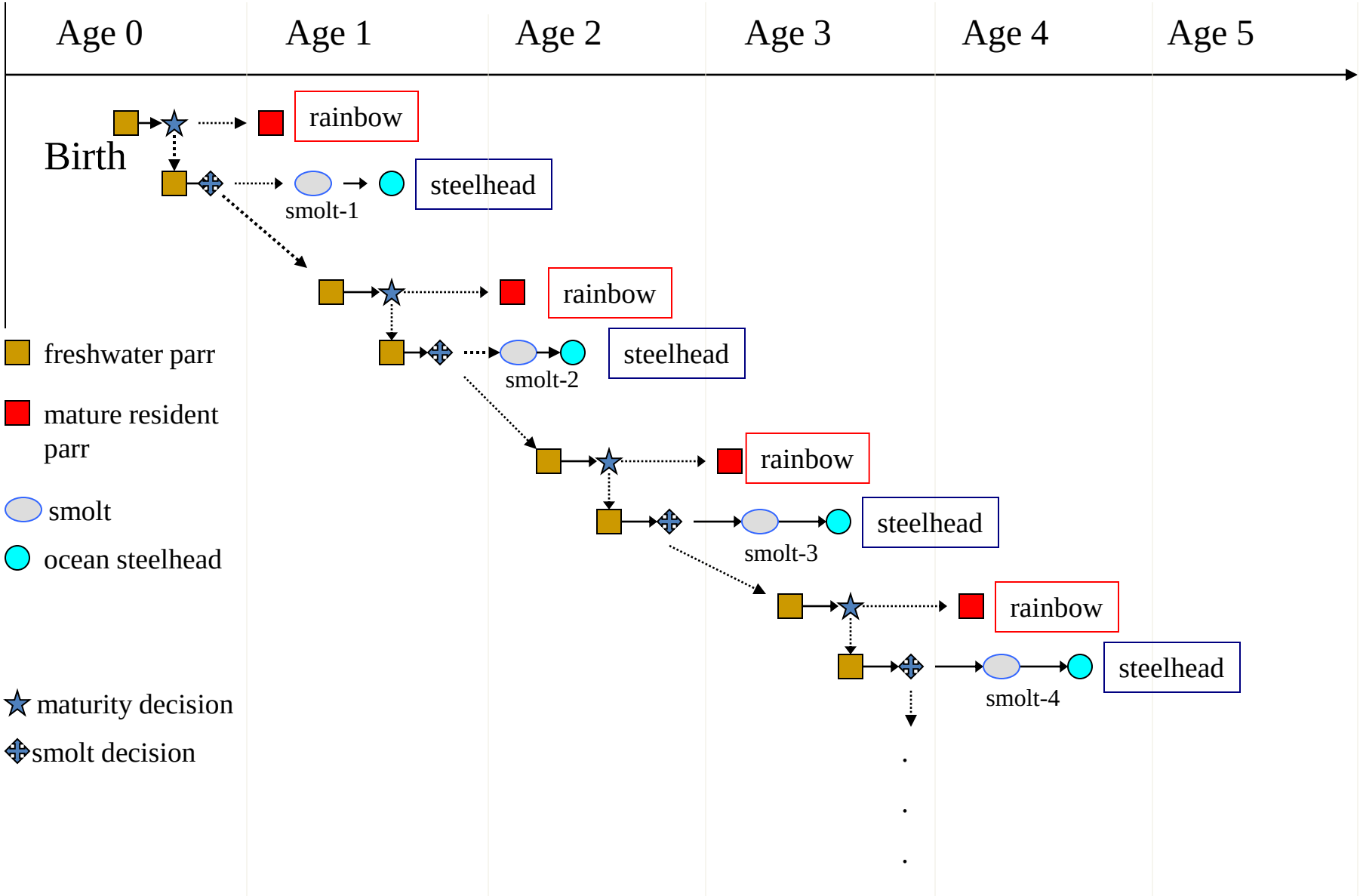
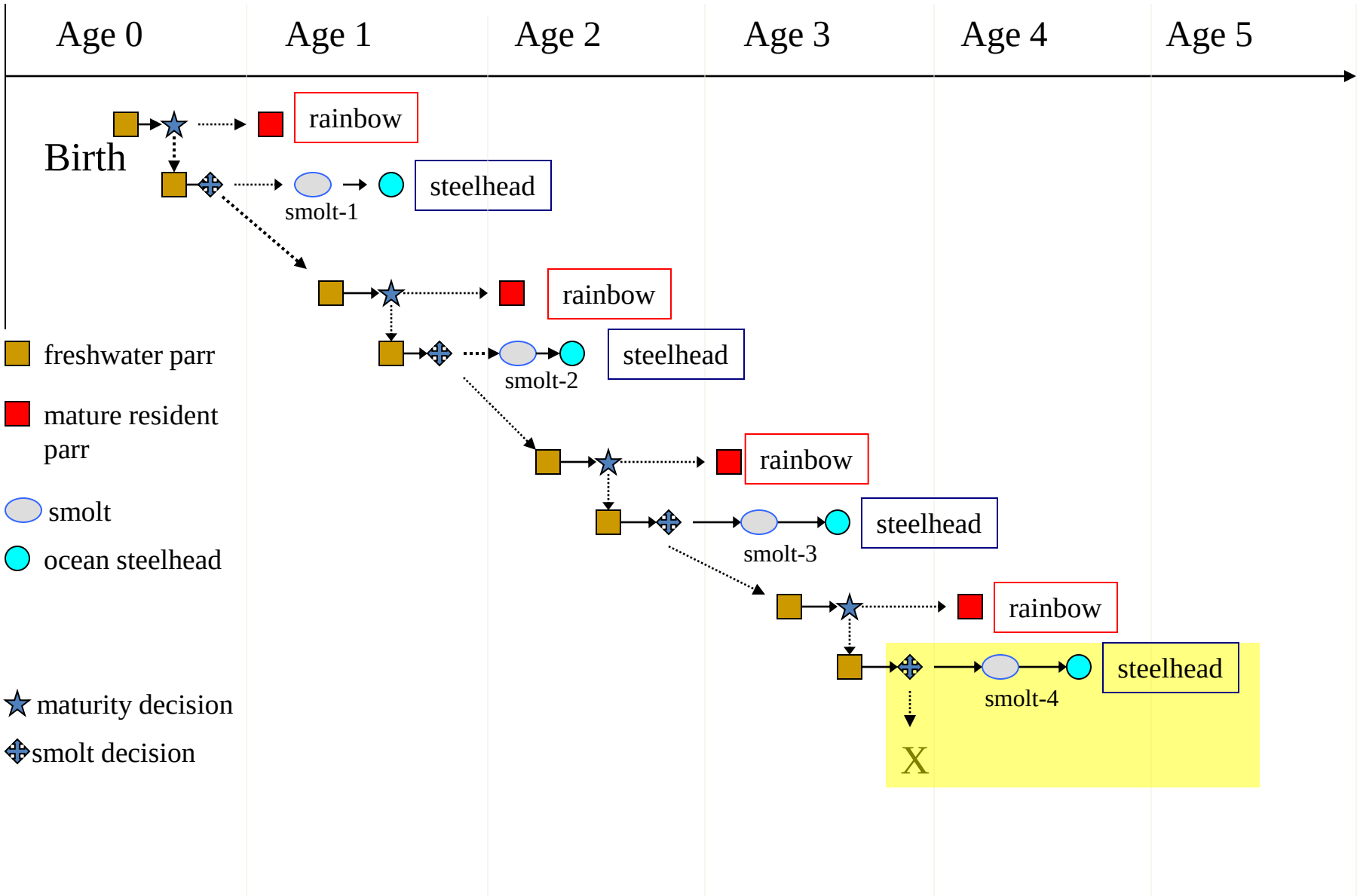

Age 0
Age 1
Age 2
Age 3
Age 4
Age 5
Birth
rainbow
smolt-1
1.1
1.2
1.3
1.4
?
rainbow
smolt-2
2.1
2.2
2.3
rainbow
smolt-3
3.1
3.2
3.3
freshwater parr
mature resident parr
smolt
immature ocean
mature ocean
maturity decision
smolt decision


Age 0
Age 1
Age 2
Age 3
Age 4
Age 5
Birth
rainbow
steelhead
smolt-1
rainbow
steelhead
smolt-2
rainbow
steelhead
smolt-3
rainbow
steelhead
smolt-4
freshwater parr
mature resident parr
smolt
ocean steelhead
maturity decision
smolt decision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steelhead
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ocean steelhead
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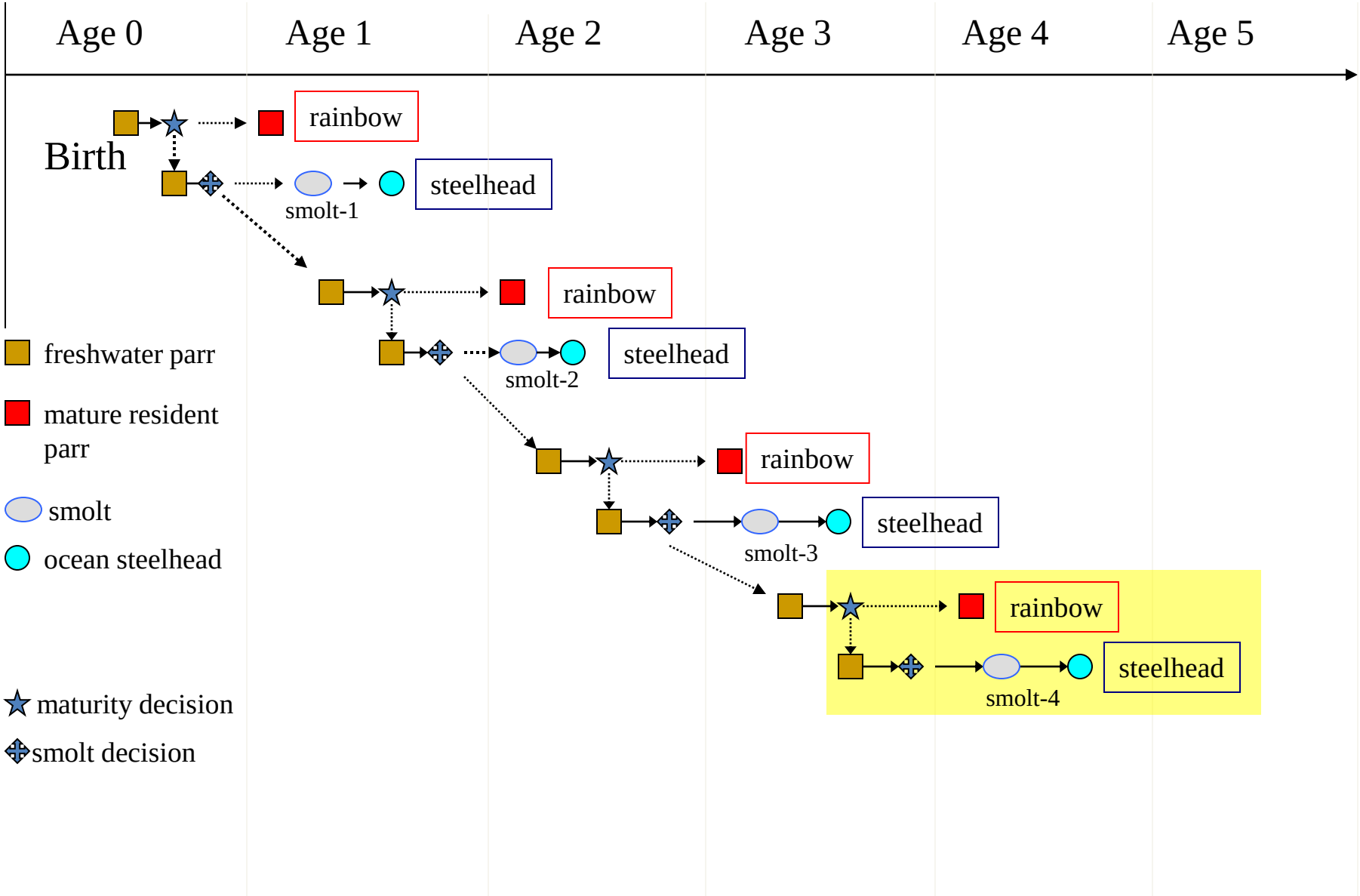
smolt decision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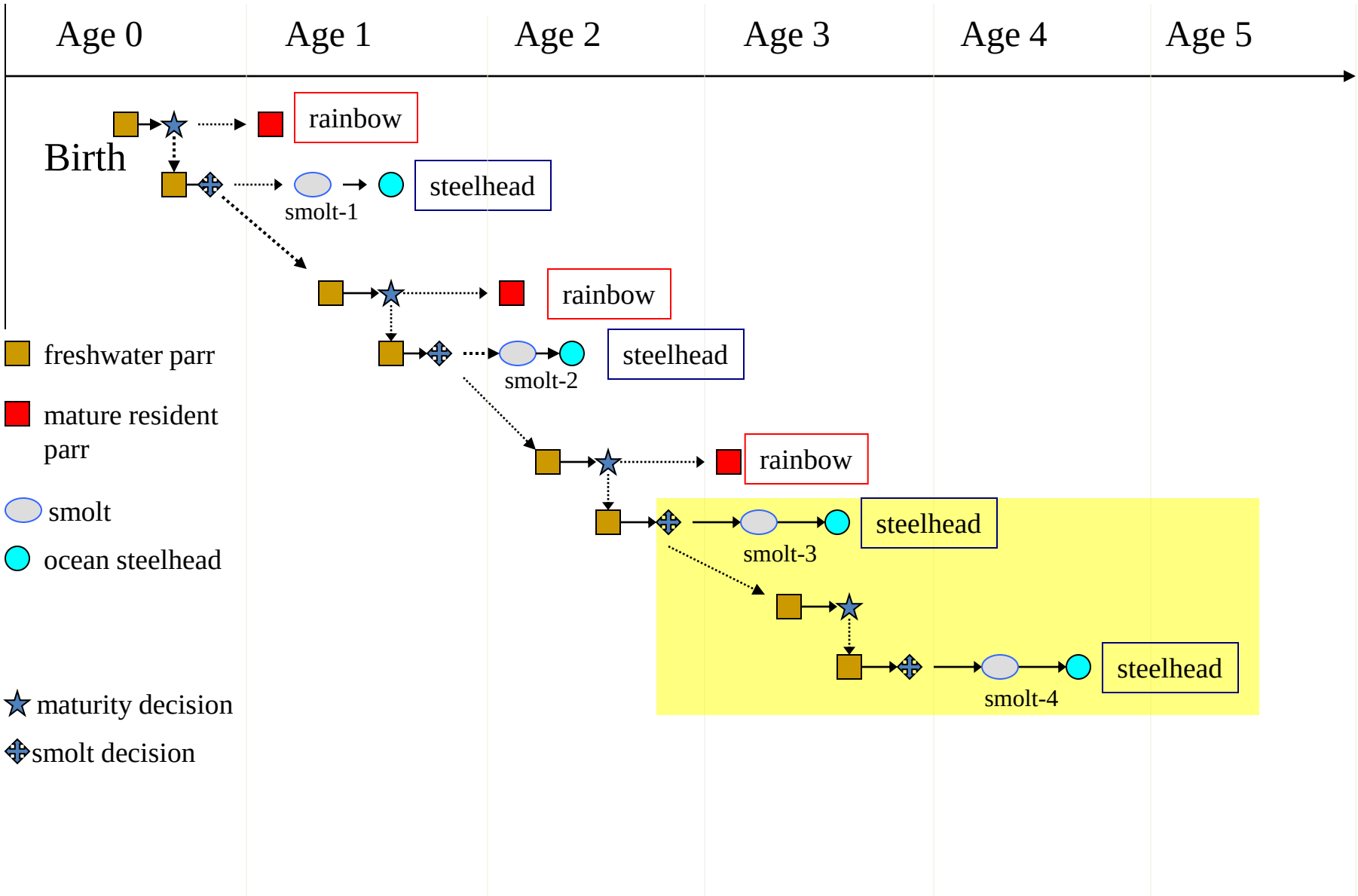
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Dynamic State Variable Model

- *F(l,g,e,t)*
  - *F*: expected lifetime fitness (eggs produced)
  - *l*: size
  - *g*: developmental switch, maturity
  - *e*: developmental switch, smolting
  - *t*: time
- *l'(l,g,e,t)* – expected future size at time *t*+1
- *s(t)* - survival to time *t*+1

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Dynamic State Variable Model

- Spawning
  - $F(l,1,0,T)=R_r(l)$
  - $F(l,1,0,t)=R_r(l)+s(t)F(l'(l,1,0,t),1,0,t+1)$
- Emigrating
  - $F(l,0,1,t)=S(l)R_s$
- Updating outside windows
  - $F(l,g,e,t) =s(t)F(l'(l,g,e,t),g,e,t+1)$
- Decisions
  - $F(l,0,0,t) =\max_{g,e} s(t)F(l'(l,g,e,t),g,e,t+1)$

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Model Inputs

- Survival (freshwater, migration, ocean)
  - Primarily literature values + sensitivity analyses
  - Seasonal variation can be accommodated
- Growth (as a model input, or submodel)

$$\frac{dW}{dt} = \phi\left(T\left(t\right)\right)cW\left(t\right)^{0.86}\frac{a}{\kappa + a} - \left(1 + a\right)\alpha e^{0.071T\left(t\right)}W\left(t\right)$$

  - Energy balance, optimal foraging
  - Temperature dependencies and allometries from literature, gut capacity and BMR from lab fits
- Fecundity
  - Size-egg relationship, kelt rate
- Timing
  - Of windows, of migrations, of spawning

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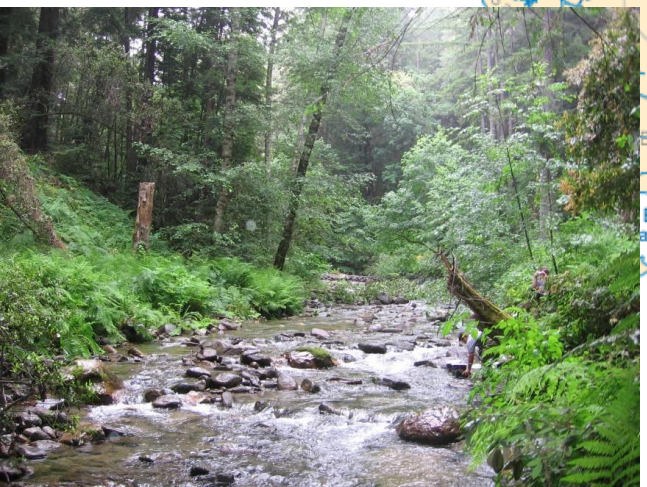
Model Outputs

- Direct
  - Smolt “decision” as function of size, growth rate
  - Maturity as function of size (emergence), growth
  - Relative fitness for alternate pathways
- Emergent
  - Size threshold for smolting
  - Distribution of life histories in a population
  - Geographic patterns in life histories
  - Selective consequences of environmental change
- More advanced
  - Timing of movements (recent ms in review at TAFS)

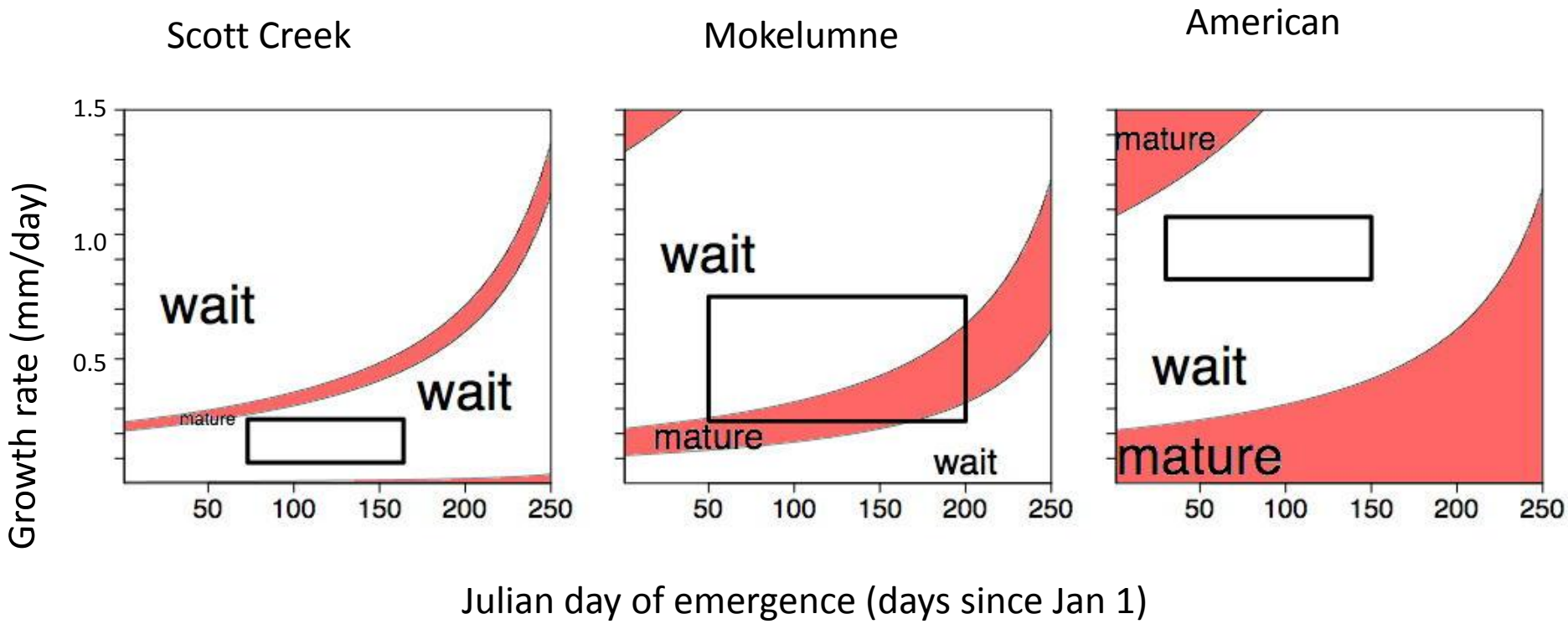
American River

Mokelumne River

Scott Creek



Maturity thresholds



Prediction: Little/no residency on Scott Creek or American River
Some residents on Mokelumne

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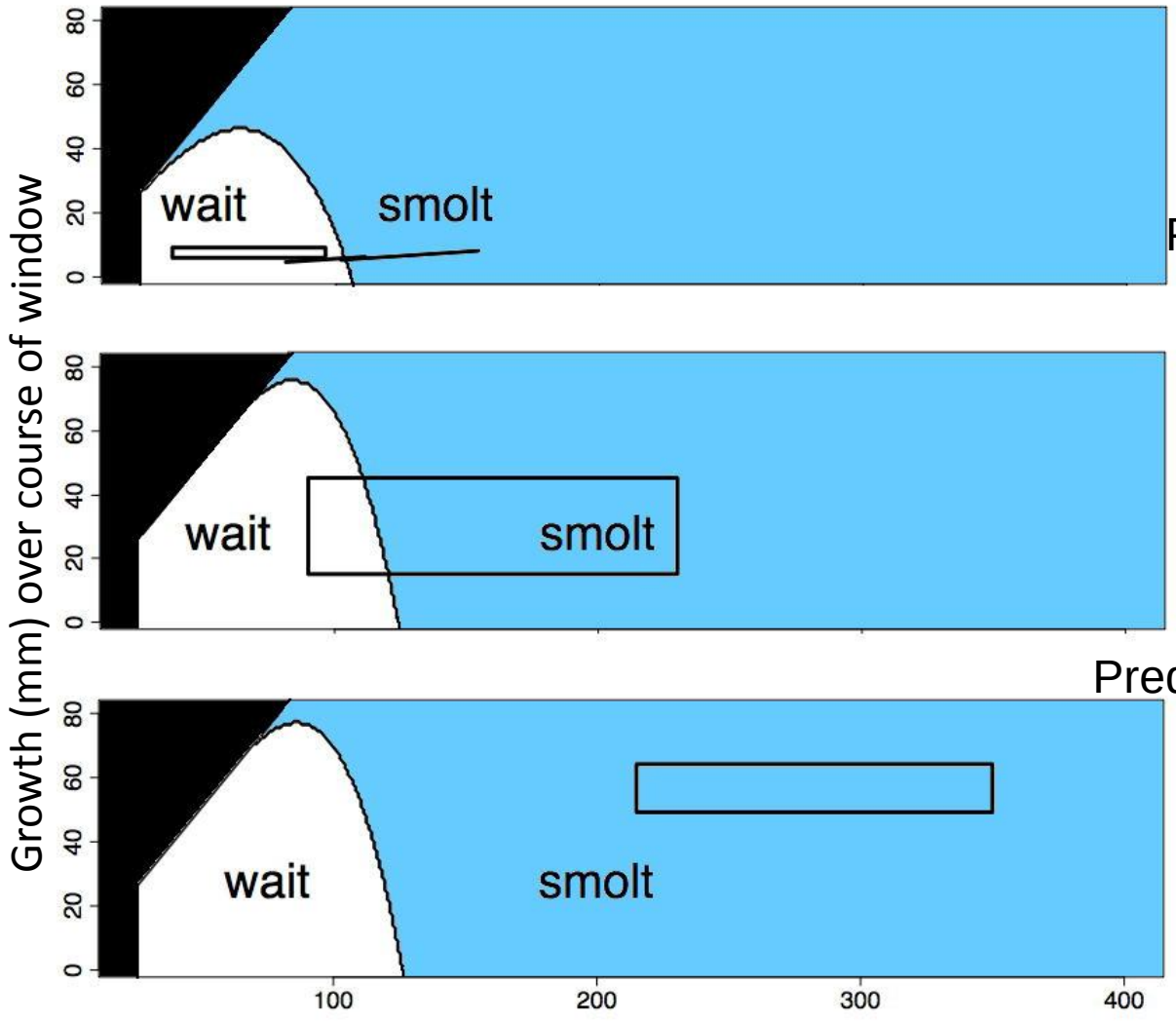
Smolt thresholds

Scott Creek



Predict: older smolts

Moke.

Predict: younger smolts
larger threshold

American

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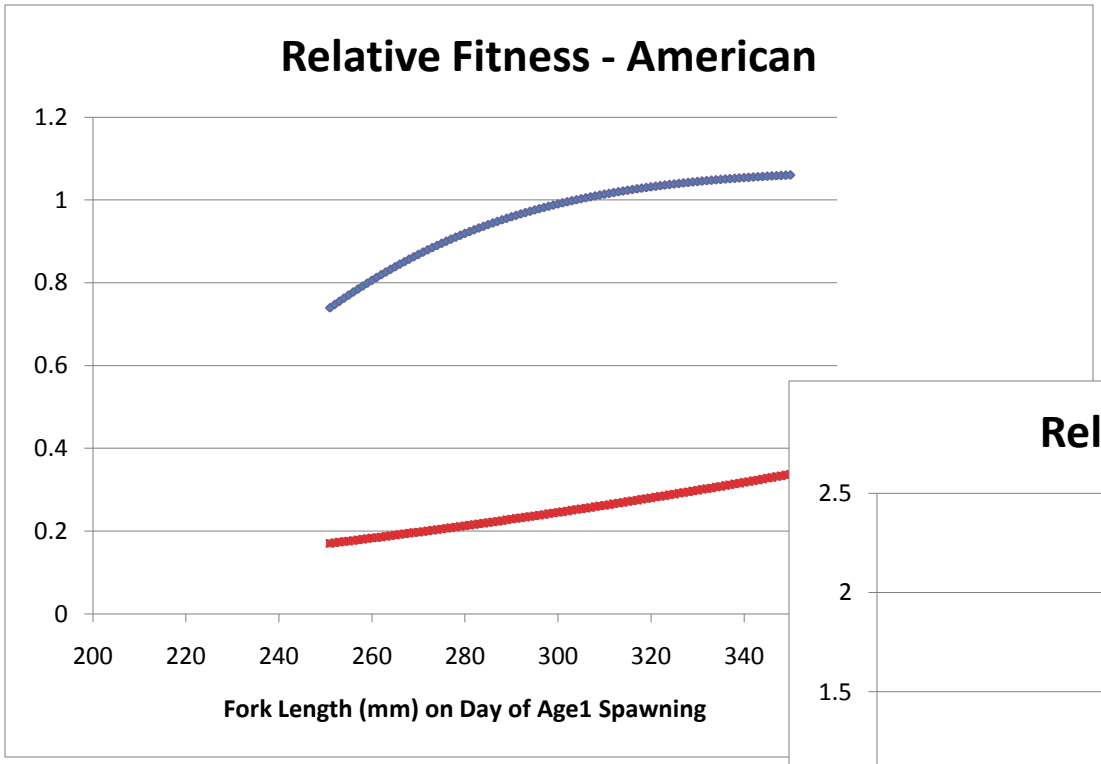
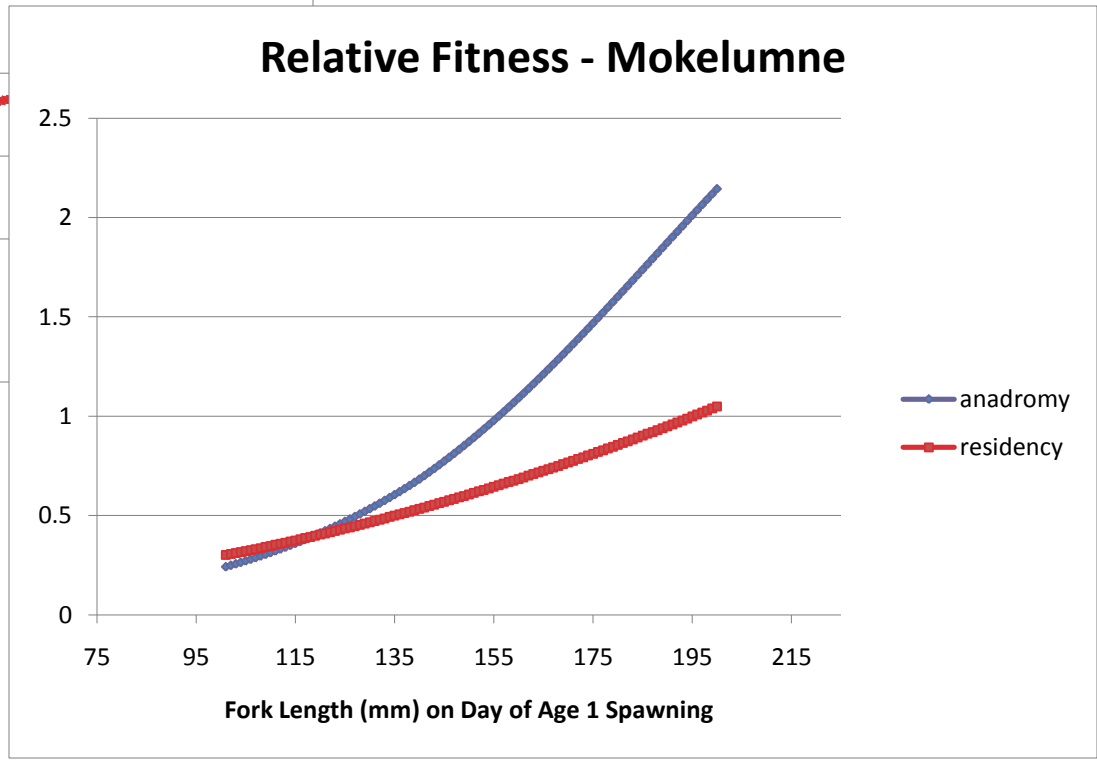
Fitness of suboptimal strategies





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Addressing Uncertainty – Sensitivity Analyses

Table 2. Life histories predicted for each river under baseline growth conditions for different survival scenarios, if female steelhead are physiologically capable of maturing as YOY and first spawning at age 1 (A) or if the first possible spawning comes at age 2 (B). When a mix of life histories is predicted, the most common phenotype is listed first. Asterisks denote the baseline scenario.

	American River			Mokelumne River		
	Emigrant/marine survival					
Freshwater survival	Low	Medium	High*	Low	Medium	High*
(A)						
Low*	Residents	Age 1 smolts	Age 1 smolts	Residents	Age 1 smolts and residents	Age 1 smolts and residents
Medium	Residents	Age 1 smolts	Age 1 smolts	Residents	Age 1 smolts, residents, and age 2 smolts	Age 1 smolts and age 2 smolts
High	Residents	Age 1 smolts	Age 1 smolts	Residents	Age 1 smolts, residents, and age 2 smolts	Age 1 smolts and age 2 smolts
Size-dependent	Residents	Residents	Residents	Residents	Residents and age 1 smolts	Age 1 smolts and residents
	American River			Mokelumne River		
	Emigrant/marine survival					
Freshwater survival	Low	Medium	High*	Low	Medium	High*
(B)						
Low*	Age 1 smolts	Age 1 smolts	Age 1 smolts	Age 1 smolts and residents	Age 1 smolts	Age 1 smolts
Medium	Age 1 smolts	Age 1 smolts	Age 1 smolts	Age 1 smolts and residents	Age 1 smolts and age 2 smolts	Age 1 smolts and age 2 smolts
High	Residents	Age 1 smolts	Age 1 smolts	Residents	Age 1 smolts and age 2 smolts	Age 1 smolts and age 2 smolts
Size-dependent	Age 1 smolts	Age 1 smolts	Age 1 smolts	Age 1 smolts	Age 1 smolts	Age 1 smolts

*The baseline scenario.

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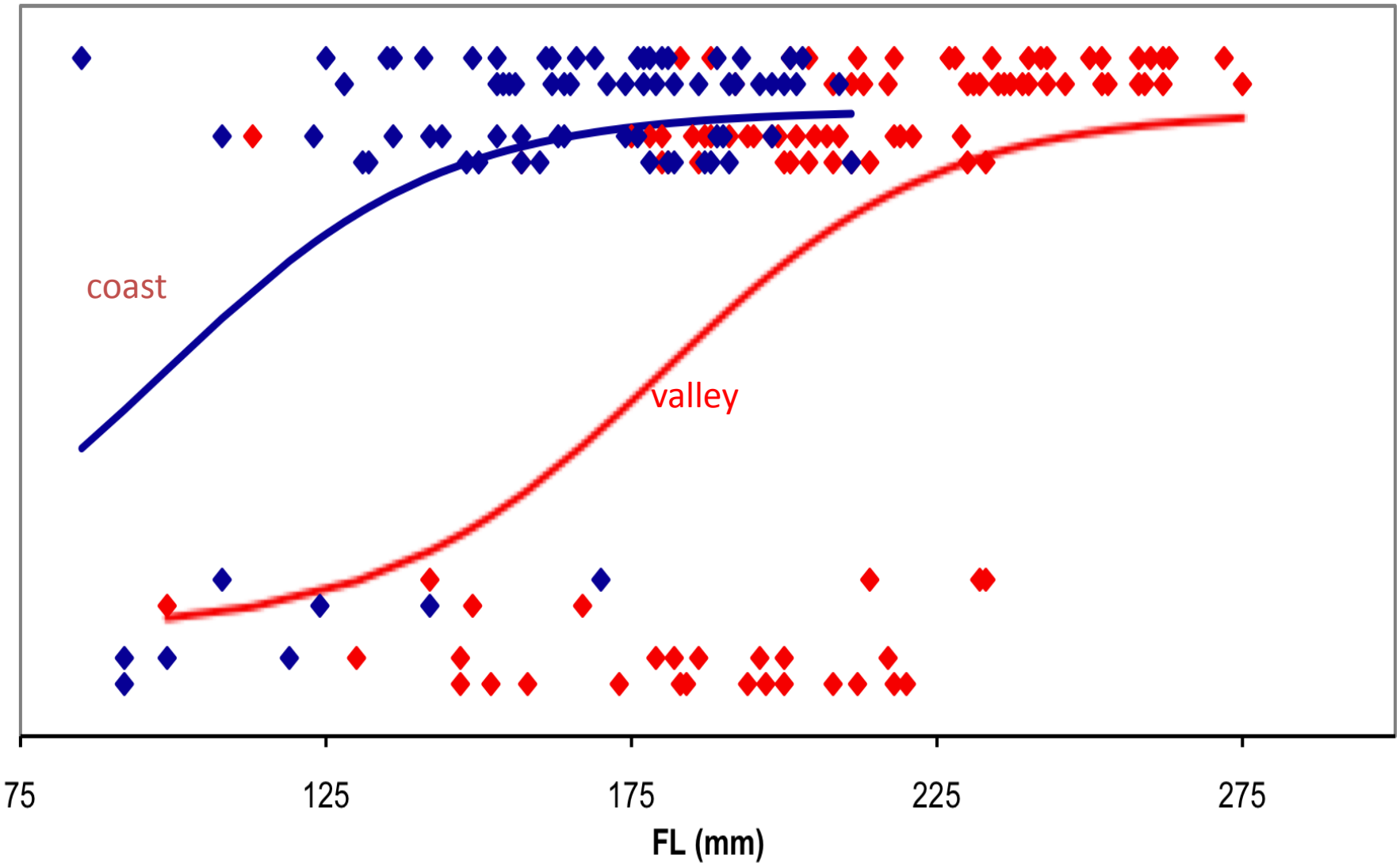
Model predictions and validation

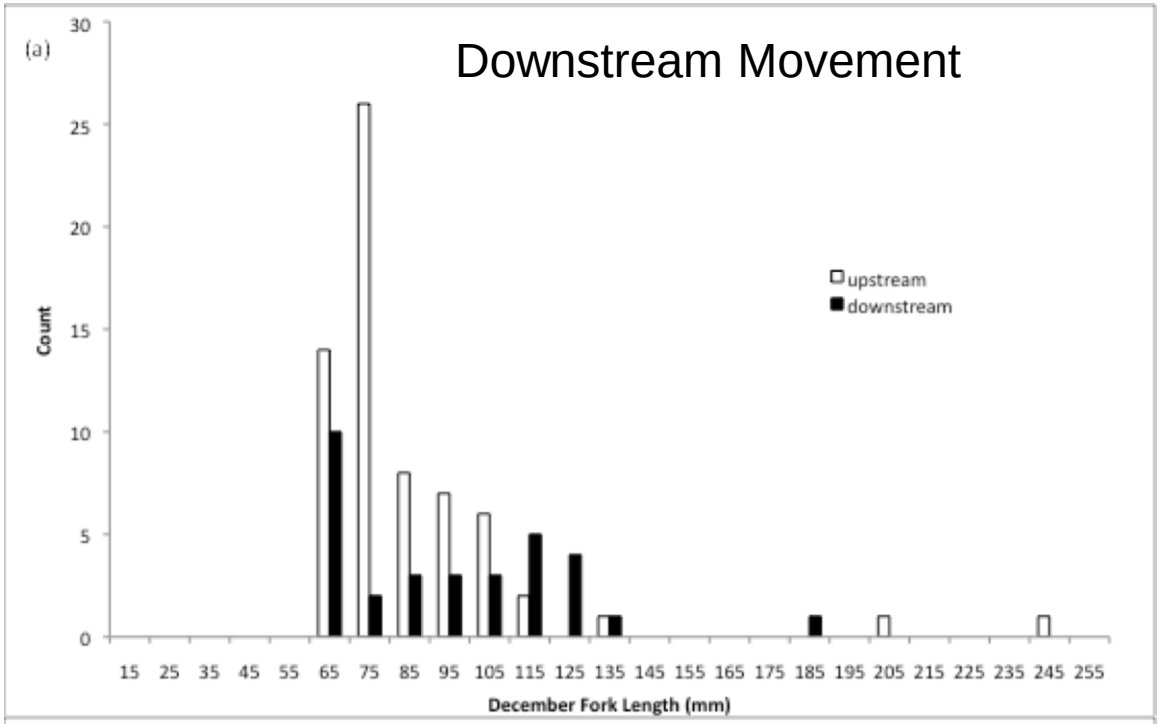
- Validation to date has largely been ability to reproduce geographic patterns
- Older anadromous fish on Scott Creek (TAFS 138:532), mix of life histories on Mokelumne (Evol App 3:221), young anadromous fish on American (Evol App 3:221)
  - Alternate explanation for Mokelumne residency
- Larger size threshold valley vs. coast (TAFS 139:1263)
- Individual life histories for Scott Creek (in review)

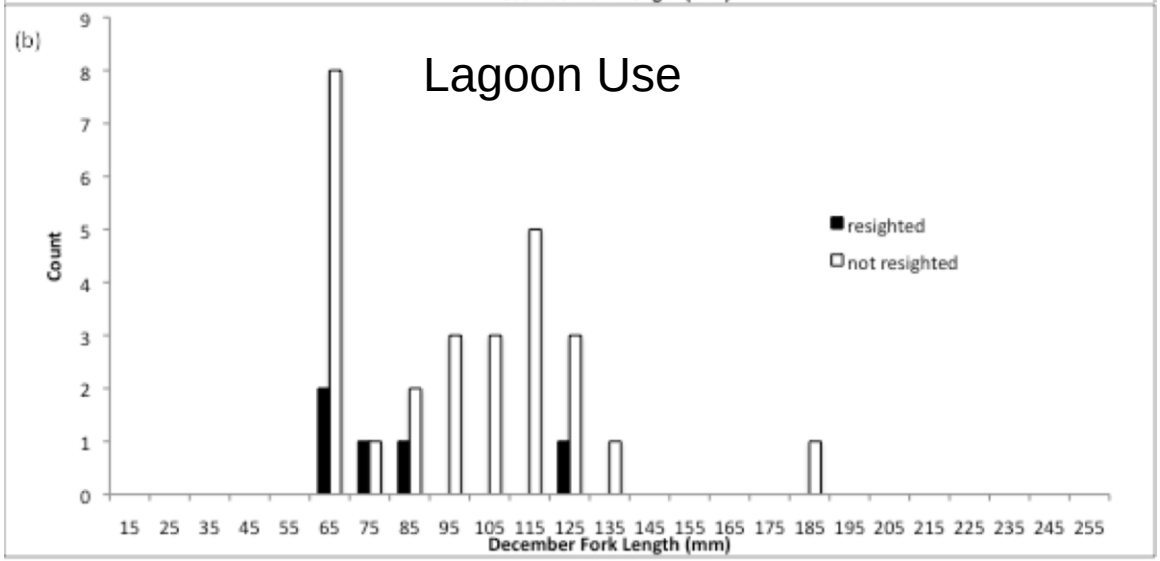
Lab Result: Saltwater Challenge Survival By Size & Strain



Beakes et al. TAFS 138:532-548

Size-dependent individual movements – Scott Creek





Developed model with weekly movement decisions: upstream, lagoon, ocean

Satterthwaite, Hayes, et al. TAFS in review

Effects of changing environment

- Short term (plastic): compare new growth vs. old thresholds (no predicted response to survival changes, but can quantify demographic costs)
  - Coast: much faster growth could yield mature parr. Easy to change average age at smolting.
  - Valley: slow growth might yield mature parr. Reduced passage survival decreases fitness.

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  - Coast: much faster growth could yield mature parr. Easy to change average age at smolting.
  - Valley: slow growth might yield mature parr. Reduced passage survival decreases fitness.
- Long term (evolutionary):
  - Both: Most sensitive to emigration survival
    - Importance of estuaries, passage through delta to preserving anadromous life history

Future directions, elaborations

- Refine functional relationship between temperature, flow, food, and growth
- Model management effects on survival
  - Join with external models of growth/survival?
- Evolutionary dynamics
- Probabilistic Reaction Norms and IPMs

Availability and Applications

- R code freely available upon request
  - satterth@darwin.ucsc.edu
  - http://www.soe.ucsc.edu/~msmangel/SteelheadSDP-TAFS.zip

- Recipients to date:
  - Planned loose adaptations to other salmon (WDFW, NOAA), more direct applications of framework/code to steelhead in Columbia (USGS, NRC postdoc applicant) and Patagonia (CONICET) and for Dolly Varden in Alaska (UW)

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University of California Santa Cruz

S. Hayes, M. Bond, and C. Hanson

MRAG Americas